

# An Alternate Air System Concept for Application in a High Pressure Turbine

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## Abstract

In 1995, the German government initiated an aerospace research programme in order to support the capabilities of German companies in the more and more challenging environment of aerospace business. Engine 3E is the research part of this overall programme concentrating on jet engines. Its aim was to develop technologies to reduce the impact of turbojet engines onto the environment, where 3E stands for Efficiency, Economy and Environment. In this research framework, one of the subprojects concerned the development of a new high pressure turbine (HPT) air system concept, which is presented in this paper.

Main objective of the air system itself is provision of sufficient cooling air for the turbine blades on the one hand and sealing of the rim between stator and rotor in the hub area against hot gas ingestion from the annulus on the other hand. The conventional BR700 family HPT air system relies on high pressure compressor (HPC) exit stage bleed air as feed for blade cooling of both HPT stages and rim sealing.

An optimised HPT rotor air system has been developed, which uses bleed air of three different HPC stages as feed for blade cooling and rim sealing. This system has the advantage to provide adequate feed pressures for the respective turbine locations. According to the required pressure level HPC exit stage bleed air is used for blade cooling of the first HPT rotor and rim sealing in front of rotor 1. Lower stage bleed air is fed through external pipes through the HPT stage 2 vanes for rim sealing in front of and behind the HPT stage 2 vanes. Bleed air of an even lower HPC stage is used for ventilation of the inner interstage cavity and blade cooling of the second stage rotor blades.

The optimised HPT air system concept additionally features a new secondary preswirl system with a brush seal and a mini disc in the interstage cavity. The mini disc is introduced to separate bleed air of different stages inside the interstage cavity. The whole concept was introduced into a BR700 family core engine and tested successfully in the altitude test facility of the University of Stuttgart. A comparison of the measured air and metal temperatures of both concepts as well as the implication on specific fuel consumption and feasibility of both concepts will be presented within the paper. Implications on manufacturing, assembly and failure behaviour will be addressed.

Key words: HPT Air System, Preswirl System, Brush Seal

## Introduction

The main objective of any jet engine is to deliver thrust to the customer in a safe and cost-efficient manner. The individual components of the engine, i.e. compressors, combustion chamber and turbines have to be matched against each other to form a very efficient, operating system. Every bit of air, which is extracted from the main gas path for other purposes than delivering this thrust has to be regarded as an unwanted deficit to this main purpose. This parasitic air requirements are illustrated in Figure 1, where air is taken from the main annulus in order to ensure the cooling of the turbine blades, the sealing of the bearing chambers and finally for controlling of the loads, acting from the different modules onto the bearings.

Additionally, the cost of air taken from an aft stage of the high pressure compressor must be considered as being more expensive, since more work has been done to it, before it is taken off the main engine cycle.

On the other hand, since the temperatures within the core of the engine are too high for the currently available materials to withstand without any additional measures, air has to be used for cooling purposes, e.g. for the turbine blades or for the cooling of the casings. Measures to reduce this loss to the overall efficiency of the engine must be one of the objectives for engine development. This may be either in the direction of

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reducing overall air requirements or taking it off a stage further downstream of the compressor, where air is 'cheaper'. This was the objective of the presented subproject within the German Engine 3E project.

The main tasks of the secondary air system can thus be summarized as being:

- delivery of cooling air to the turbine blades and vanes,
- ventilation and sealing of cavities to prevent hot gas ingestion and
- balancing of compressor and turbine forces to control bearing loads.

For this purpose, air is taken off the main annulus at different positions and led to the 'customer ports' either through the inner part of the engine along the shafts or through outside pipes for their specific needs.

### **HPT cooling concepts**

The BR700 family HPT cooling concept was originally based on using HPC exit air for blade and vane cooling as well as ventilation and rim sealing purposes for both stages of the HPT (see Figure 2). While this concept is easy to handle and reduces the possibilities for failure, it is not optimised for efficiency.

The pressure of the air needed for sealing against hot gas ingestion at the turbine annulus is dropping as the air flows along its flowpath downstream through the HPT within the engine. Using HPC exit, i.e. stage 10 air gives the possibility to use the pressure drop from one cavity to another to ventilate all cavities and to fix the individual mass flows with the cross sectional area of the flow passages. As all the cooling air for this system is passing along the casing structure and inside the annulus, there are no failure modes concerning pipe ruptures or the like.

On the other hand using stage 10 air means that the compressor has placed a lot of work into the fluid which is not made use of in the Secondary Air System. Furthermore the temperature of stage 10 air is higher than the one of lower stages.

To optimise the efficiency of the cooling air system in terms of SFC and temperature distribution, it is necessary to use different sources of cooling air. The new HPT cooling concept (see Figure 3) uses three different cooling air sources, stages 6, 8 and 10.

Compressor exit air is needed for blade cooling of the HPT nozzle guide vane (NGV) 1 and rotor 1 blade and the rim sealing in front of the stage 1 disc as only this fluid provides enough pressure. To improve the system in front of the stage 1 disc, a brush seal replaced the conventional labyrinth seal to reduce the unwanted parasitic air. The amount of mass flow saved is introduced in a low radius preswirl nozzle into the system, hence reducing the disc temperature in this region.

The pressure drops very rapidly in the HPT and therefore stage 6 cooling air is sufficient for HPT rotor 2 blade cooling. Therefore this air is taken between the LP and HP shaft and inserted into the cavity between 1<sup>st</sup> and 2<sup>nd</sup> stage discs. However, since stage 6 air does not provide a pressure level sufficient to seal the rim in the rear of rotor 1 disc, it is necessary to divide the interstage cavity into two regions, the inner region ventilated by stage 6 air and the outer region ventilated by stage 8 air.

The means to divide the interstage cavity is the use of a mini disc with a labyrinth seal on the outside. Since both, stage 6 and 10 cooling air is taken through inside the annulus, there is no place to take the third cooling air source along inside the annulus into the HPT. Therefore stage 8 air is taken via external pipes to the second stage NGV for cooling of this NGV and part of it is guided into the outer region of the interstage cavity. It is then ejected to the front side of the NGV where part of it seals the gap behind the rotor 1 disc rim and the rest flows through the labyrinth seal to seal the gap in front of the rotor 2 disc rim.

The HPT new cooling concept makes it possible to replace about 5% of the core mass flow with lower stage cooling air. This has on one side a positive impact on the SFC on the other hand the lower cooling air temperature of the lower stages reduces the temperature level of the affected parts with its impact on the life of these parts.

The advantages gained by this new HPT cooling concept have to be paid for with a more complex system, more parts and additional failure scenarios.

### **Pre Swirl System**

The pre swirl system of the conventional system mixes air coming from a low radius labyrinth seal with pre swirled air at a radial position, which is relatively far outwards. This leads to a high relative total

temperature radially inward of the ore swirl nozzles with the resulting lifing restrictions for the HPT disc. The pre swirl system was thus changed with two main features:

- a brush seal at the inner radius, reducing the mass flow of unswirled air to a minimum
- a small pre swirl nozzle, injecting air onto the disc at a low radius

Calculations on the effect of this change for the resulting flow field and disc temperatures have been performed. One of the results is given in Figure 4. The scale is the same for both pictures, red color indicating high and blue color low temperatures. The advantage can clearly be seen all over the disc surface, especially in the lower radius region, where the small pre swirl nozzle shows a good effect. The level of temperature could be clearly reduced and additionally is the distribution of the temperature much smoother, which leads to less load on the disc, increasing the life expectations for this critical part.

Starting from these investigations, a brush seal had to be selected, which was capable to fulfil the requirements of the core engine test. For this, a separate research package was given to the University of Oxford. In collaboration with RR plc., appropriate experience and hardware was available here. First of all, three different configurations have been tested in order to identify a reliable, however not optimum, seal configuration for the core test. After the decision, which seal to take, a more detailed investigation by means of run down and endurance testing has been performed, ending up in a set of 10 different configurations being assessed. For this, typical environmental conditions as given for the core engine have been used.

The principle setup of the brush seals is given in Figure 5. Both straight and pressure balanced configurations have been looked at. The additional parameters, which have been tested, were:

- lay angle
- bristle diameter
- number of layers
- distance to backing plate
- rotor clearance

It could be found, that the original decision for the hardware, which was tested in the core engine, was a very good choice in terms of reliability. The result from the endurance tests for this seal is given in Figure 6. The parameters are plotted versus time. The shaft was accelerated and after reaching steady conditions, a rundown test was performed. This was combined with a pulsing, trying to bring the seal to blowdown. It was identified, that due to vibration effects of the shaft, the seal showed a step change in sealing performance at roughly 60 seconds. The overall performance of the seal was within the expectations. Concerning the pulsed rundown behaviour, the seal showed a very high resistance against blowdown and thus was the perfect choice for the core test.

The results for all tested configurations can be summarized in Figure 7, showing contact pressure of the seal versus effective clearance. This gives a good indication on the leakage, which must be expected from the seals. Seal 1 was chosen for the core engine, which is an average seal in this plot. More advantageous from this point of view would for example be seal configurations 2.

### **Thermal Behaviour**

One of the objectives of this project was also a reduction of the temperatures, which are seen by the HPT disc. The pre swirl system, as described above, leads already to a much smoother temperature distribution on the disc surface as well as to a lower level. But since the new concept also uses air of a lower temperature for the interstage cavity than the conventional concept, it was expected, that this additionally would lead to a benefit in terms of metal temperatures on the disc.

The core engine was equipped with a large number of metal temperature sensors, especially aiming to measure the temperature on the rotating parts. The test performed at the altitude test facility at the University of Stuttgart proofed the expectation to be right. Figure 8 shows the metal temperatures of the conventional cooling concept compared to the new concept. This data is matched to the measured temperatures within the respective engines and shown in the same scale. It clearly represents a real benefit. Beside the better distribution upfront of rotor 1, rotor 2 experiences a significantly lower temperature from the bore to the blade platforms. Additionally, the distribution of the temperature within the disc became much more uniform. This is especially important in the bore region.

### **Failure Mode Investigation**

The new concept takes compressor air from three different positions. Two of these mass flows can be led to their respective sinks internally of the engine. Stage 8 air, however, must be led to the interstage cavity via external pipes. This on the one hand gives additional failure scenarios, which have to be looked at, which are not present in the conventional concept. On the other hand, it gives the opportunity to control the flow to the outer interstage cavity exactly via restrictors.

For the core engine test, the opportunity was taken to investigate the effect of more or less flow to this cavity onto the air temperature upfront of the second stator row of the turbine. For this, restrictors with different diameters have been incorporated into the pipes and the resulting air temperatures at the outer interstage cavity have been measured. Figure 9 shows the results of these investigations as a delta temperature relative to compressor exit temperature versus HP spool speed. The delta temperature to the compressor exit is obviously nearly no function of the HP spool speed, since with increasing spool speed, the delta remains more or less constant. The temperature level increases with a reduction of the restrictor diameter. This has to be expected, since less air is provided to the cavity, giving less sealing against ingestion of hot air from the annulus into the cavity. Although this is restricted to local ingestion due to the circumferential variance in pressure in the annulus dictated by the nozzle guide vanes, it increases the overall level of the temperature.

For the worst scenario, which has been simulated, i.e. the pipe rupture, the delta temperature becomes dependent on the the HP spool speed. An increase in spool speed also increases the delta temperature. The strong increase in the level indicated, that massive hot gas ingestion must be present. This leads to a difference in the worst case of 40K compared to the same restrictor with no pipe rupture considered. It has already been described, that the overall temperature level at all positions is significantly lower compared to the conventional concept. Since this decrease in overall temperature is bigger than the given 40K, the failure mode assessment for the new concept is able to cover the pipe rupture scenario.

### **Conclusions**

An alternate concept has been presented for the cooling of a high pressure turbine. Various aspects have been included in the development, which lead to advantages in different aspects. The overall efficiency of the engine could be increased due to the fact, that 'cheaper' air is taken from the compressor to fulfil the requirements of the secondary air system.

However, the new concept also exhibited some shortfalls. The number of parts is bigger, although the total weight can be reduced due to the better conditions for the HPT discs. The costs of this concept are higher than for the conventional system. Additionally, the flange connecting the two HPT rotor discs, must be bolted from the inner radius. For a single development engine, such as the core, this is possible. However, for a production environment, this procedure proofed to be difficult in terms of handling.

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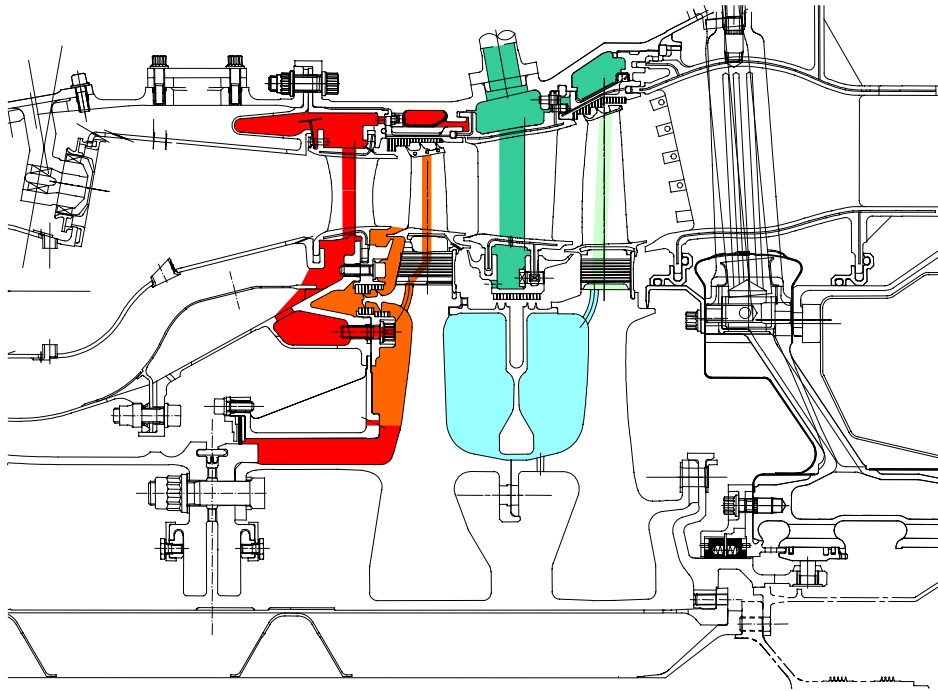


Figure 3: Optimized HPT Cooling Concept

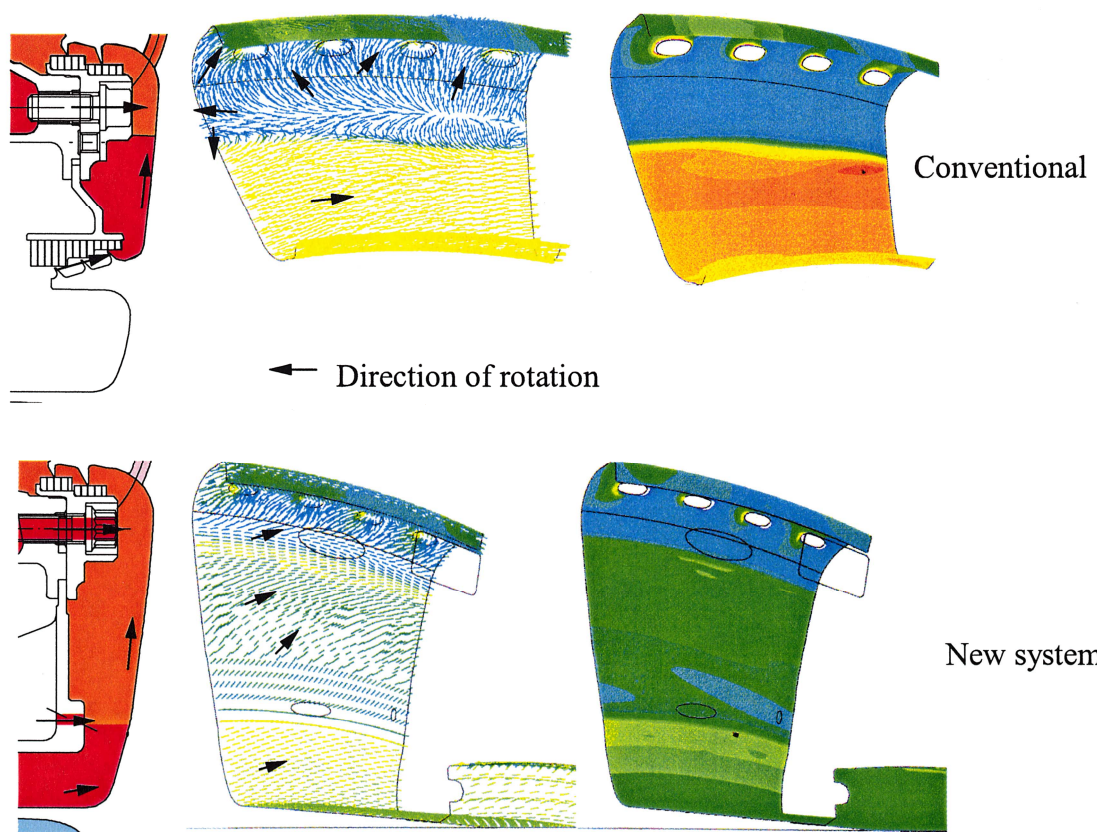


Figure 4: Effect of new pre swirl system on flow field and temperature distribution on the HPT disc



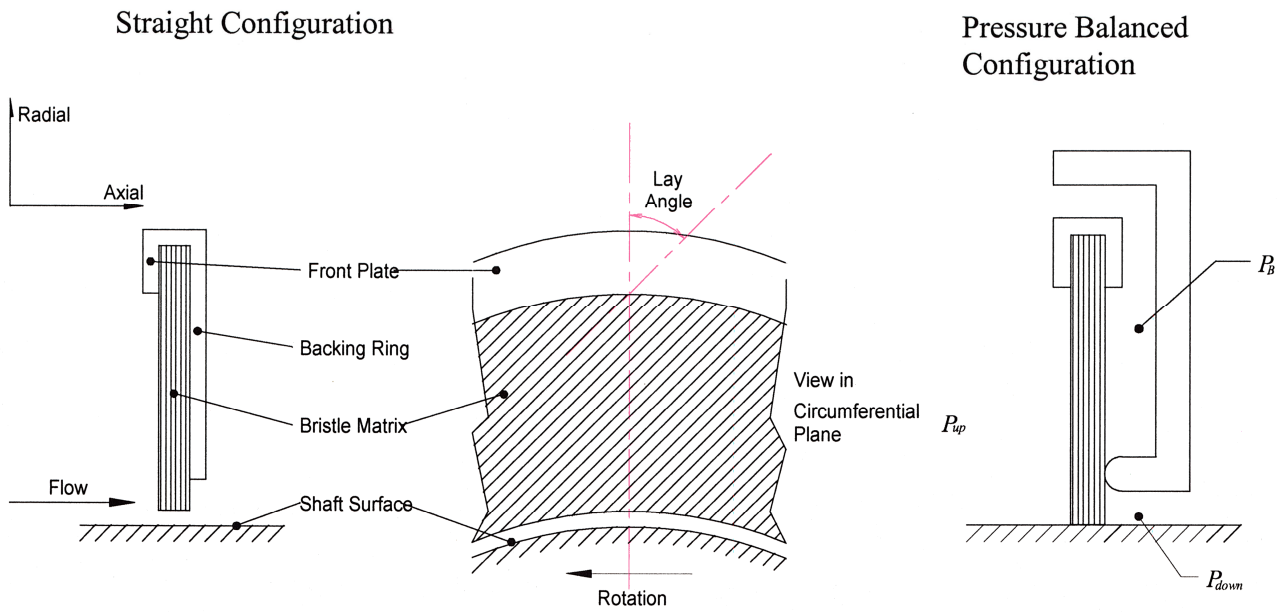


Figure 5: Brush seal configurations

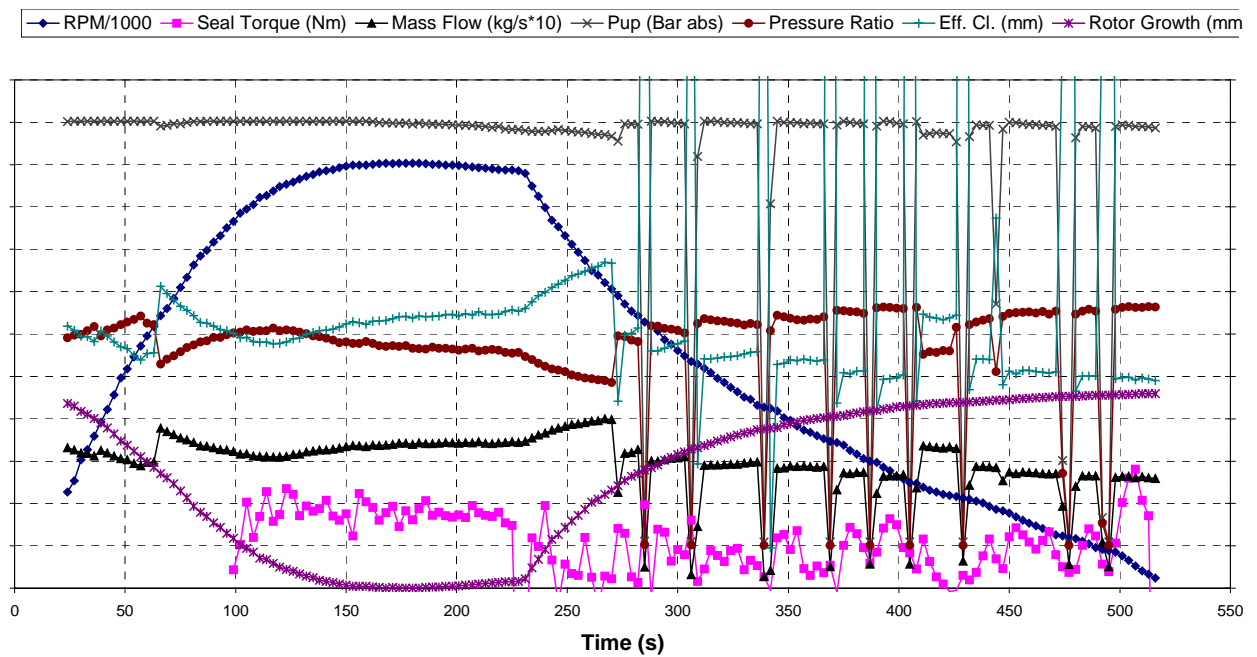


Figure 6: Endurance Test Results for the core engine brush seal



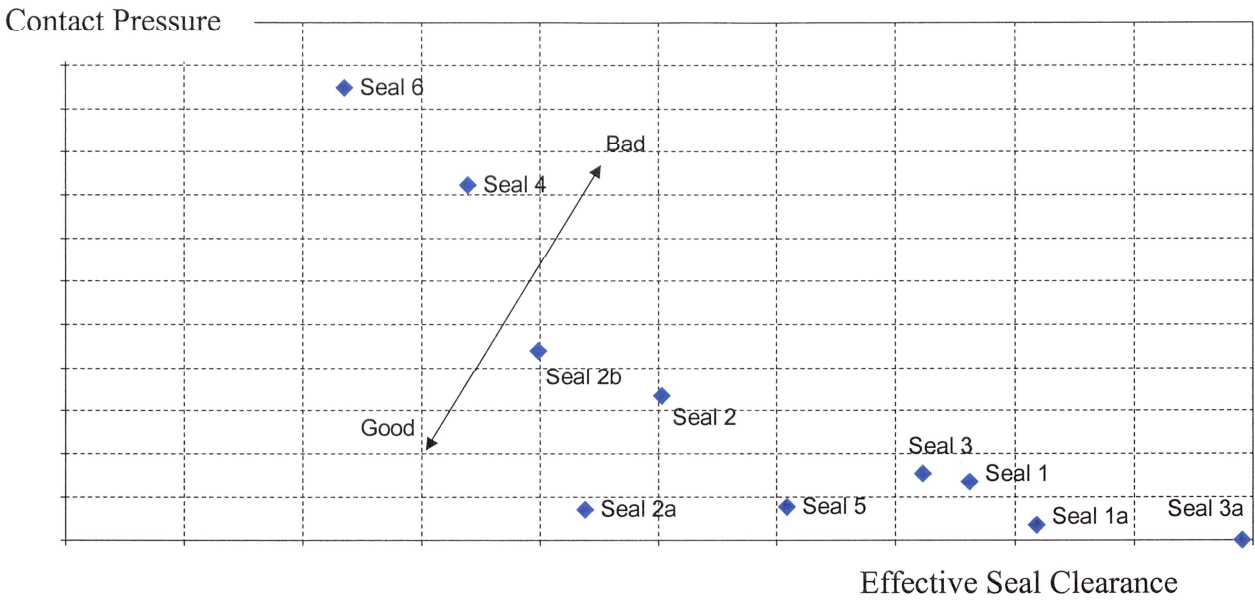


Figure 7: Contact pressure versus effective seal clearance

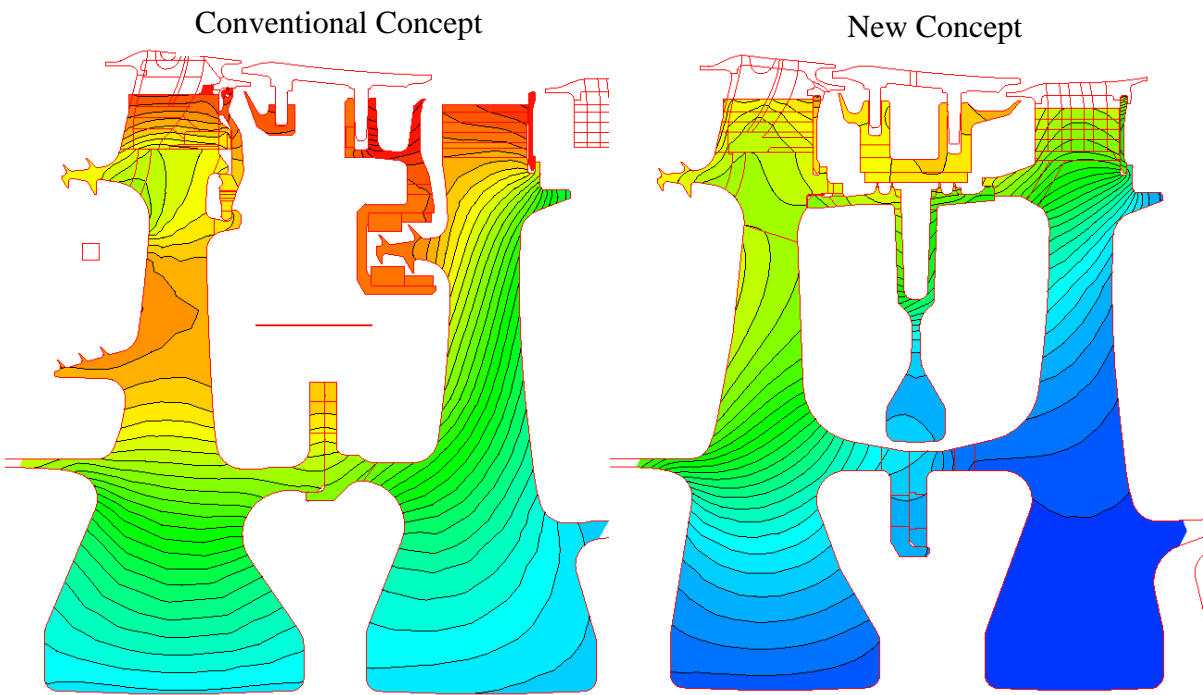


Figure 8: Comparison of metal temperatures between the conventional and the new cooling concept

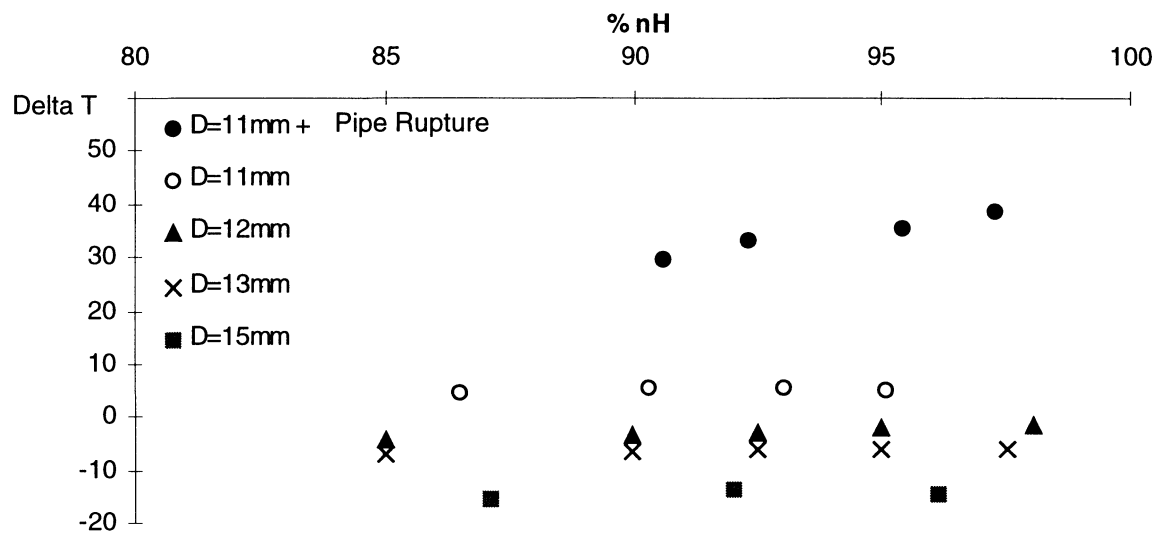


Figure 9: Temperature in the outer interstage cavity for different restrictor diameters

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Question:

- 1 Is the feeding pressure of the second stage rotor blade modified by the optimised HPT cooling concept?
- 2 Did occur changes in the cooling of this 2<sup>nd</sup> stage rotor blade?

Answer:

- 1 Yes, due to different sources for provision of air, this is to be expected, unless special measures are taken. This was not necessary in the presented case, since due to the overall research activities, all parameters had to be locked at and accordingly adjusted.
- 2 Yes. Although this must not be necessarily true. Mandatory for the blade cooling is the presence of a certain pressure ratio across the blade (i.e. feed position & annulus) to fulfil the turbine blade cooling requirements.